UNITED STATES PATENT APPLICATION

for

MASK REPAIR WITH ELECTRON BEAM-INDUCED CHEMICAL ETCHING

Inventors:

Ted Liang and Alan Stivers

Prepared by:

BLAKELY, SOKOLOFF, TAYLOR & ZAFMAN
12400 Wilshire Boulevard
Seventh Floor
Los Angeles, CA 90025-1026
(408) 720-8598

Attorney Docket No.: 042390.P11354

"Express Mail" mailing label number: EL672774675/US
Date of Deposit: June 29, 2001
I hereby certify that I am causing this paper or fee to be deposited with the United States Postal Service "Express Mail Post Office to Addressee" service on the date indicated above and that this paper or fee has been addressed to the Assistant Commissioner for Patents, Washington, D. C. 20231

Teresa Edwards
(Typed or printed name of person mailing paper or fee)

Teresa Edwards
(Signature of person mailing paper or fee)

June 29, 2001
(Date signed)

BACKGROUND OF THE INVENTION

1. FIELD OF THE INVENTION

The present invention relates to the field of semiconductor integrated circuit manufacturing, and more specifically, to a method of fabricating and repairing a mask with electron beam-induced chemical etching.

2. DISCUSSION OF RELATED ART

After coating photoresist on a semiconductor wafer, a scanner may be used to expose the photoresist to radiation, such as deep ultraviolet (DUV) light with nominal wavelength of 248 nanometers (nm), 193 nm, or 157 nm. The wafer is sub-divided into contiguous identical fields and a reduction projection system is used to scan light across a mask and onto each field. One or more integrated circuit (IC) chips is fabricated in each field. The mask, which may be transmissive or reflective, determines the pattern to be transferred to the photoresist as a result of the exposure followed by a develop process.

Using a Phase-Shifting Mask (PSM) and Optical Proximity Correction (OPC) with DUV light will allow printing of features with a critical dimension (CD) of 100-180 nm. However, Next Generation Lithography (NGL) is required to print features with even smaller CD. Extreme Ultraviolet (EUV) lithography, a leading candidate for NGL, uses exposure light with a central wavelength in the range of 10–15 nm.

An EUV scanner may have 4 imaging mirrors and a Numerical Aperture (NA) of 0.10 to achieve a CD of 50–70 nm with a depth of focus (DOF) of about 1.00 micrometer (um). Alternatively, an EUV scanner may have 6 imaging mirrors and a NA of 0.25 to print a CD of 20-30 nm with a reduction in DOF to about 0.17 um.

A DUV or EUV mask is inspected for defects during fabrication. Repair of critical defects is performed with a focused ion beam (FIB) tool having a Gallium liquid metal ion source. A clear defect is covered up by depositing Carbon or a metal, followed by trimming with gas-assisted etch (GAE). An opaque defect is repaired with physical ion sputtering or GAE with ion bombardment. The process to remove opaque defects should have adequate etch selectivity to the underlying layer. The underlying layer is quartz in a transmissive mask for DUV or a buffer layer in a reflective mask for EUV.

FIB may damage a mask during the scan to search for defects or during the repair of defects. The repaired portions of the mask may be roughened by sputtering. Organic contamination may be deposited on the surface of the mask. Gallium ions may be implanted into underlying layers. Gallium absorbs strongly at 157 nm and at EUV wavelengths, thus decreasing the transmission in a transmissive mask, such as a 157 nm DUV mask, or decreasing the reflectivity in a reflective mask, such as an EUV mask. Underlying layers of the mask may be further damaged by knock-on of atoms by Gallium.

Damage to a mask becomes more problematic as the CD of the features on the mask shrinks. Lowering the acceleration voltage in the FIB will reduce the penetration range of Gallium ions, but etch selectivity and spatial resolution are compromised. Limiting imaging time and overscan area can reduce damage, but repair may also be adversely affected. Post-repair treatment, such as wet etch of the quartz substrate in a 157 nm DUV mask or the buffer layer in an EUV mask, will remove implanted Gallium ions, but the underlying material may become pitted. If sufficient material is removed, a phase error may also be introduced.

Thus, what is needed is an apparatus for and a method of fabricating and repairing a mask without damage.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 (a) – (d) are illustrations of a cross-sectional view of an EUV mask blank formed according to the present invention.

Figure 2 (a) – (d) are illustrations of a cross-sectional view of an EUV mask formed according to the present invention.

Figure 3 is an illustration of a cross-sectional view of an EUV mask of the present invention.

Figure 4 is an illustration of a cross-sectional view of an apparatus for repairing opaque defects with electron beam-induced chemical etch according to the present invention.

DETAILED DESCRIPTION OF THE PRESENT INVENTION

In the following description, numerous details, such as specific materials, dimensions, and processes, are set forth in order to provide a thorough understanding of the present invention. However, one skilled in the art will realize that the invention may be practiced without these particular details. In other instances, well-known semiconductor equipment and processes have not been described in particular detail so as to avoid obscuring the present invention.

A mask is used in lithography to print a desired pattern in photoresist on a wafer. Deep ultraviolet (DUV) lithography uses a transmissive mask for exposure with light having a wavelength of 248 nm, 193 nm, or 157 nm. Extreme ultraviolet (EUV) lithography uses a reflective mask for exposure since nearly all condensed materials are highly absorbing in the EUV wavelength range of 11-15 nm.

The desired pattern is defined in a DUV mask by selectively removing portions of an opaque Chrome layer to uncover a transparent quartz substrate. The desired pattern is defined in an EUV mask by selectively removing portions of an absorber layer to uncover a multilayer mirror on a substrate.

A DUV mask or an EUV mask is inspected for defects as part of the mask fabrication process. The inspection is usually done with DUV light. A defect may appear clear or opaque. A defect is considered critical if its size, shape, or location may significantly affect the print fidelity and quality of the mask features in the vicinity. A critical defect must be repaired or else the yield may be degraded on the structure being fabricated with the mask. The present invention includes an apparatus for and a method of repairing opaque defects on a DUV mask or an EUV mask without damage to underlying layers.

Various embodiments of a method of fabricating and repairing an EUV mask according to the present invention will be described. First, a substrate **1100** having a low coefficient of thermal expansion (CTE), a smooth surface, and a low

defect level is used as the starting material for an EUV mask of the present invention. An embodiment is shown in **Figure 1 (a)**. The substrate **1100** may be formed out of a glass-ceramic material with the desired properties.

Second, a multilayer (ML) mirror **1200** is formed over the substrate **1100** since an EUV mask operates on the principle of a distributed Bragg reflector. An embodiment is shown in **Figure 1 (b)**. The ML mirror **1200** includes about 20–80 pairs of alternating layers of a high index of refraction material **1210** and a low index of refraction material **1220**. The thickness uniformity should be better than 0.8 % across the substrate **1100**.

In one embodiment, the ML mirror **1200** includes 40 pairs of alternating layers of a high index of refraction material **1210** and a low index of refraction material **1220**. The high index of refraction material **1210** may be formed from about 2.8 nm thick Molybdenum while the low index of refraction material **1220** may be formed from about 4.1 nm thick Silicon. As needed, a capping layer **1230**, such as about 11.0 nm thick Silicon, may be formed over the ML mirror **1200** to prevent oxidation of Molybdenum at the upper surface of the ML mirror **1200** in an EUV mask. The ML mirror **1200** can achieve a peak reflectivity of about 60-75 % at the EUV central illumination wavelength of about 13.4 nm.

Ion beam deposition (IBD) or direct current (DC) magnetron sputtering may be used to form the ML mirror **1200** over the substrate **1100**. IBD results in less perturbation and fewer defects in the upper surface of the ML mirror **1200** because the deposition conditions may be optimized to smooth over a defect on the substrate **1100**. DC magnetron sputtering is more conformal, thus producing better thickness uniformity, but any defect on the substrate **1100** will tend to propagate up through the alternating layers to the upper surface of the ML mirror **1200**.

Third, a buffer layer **1300** is formed over the upper surface of the ML mirror **1200**. An embodiment is shown in **Figure 1 (c)**. The buffer layer **1300** may have a thickness of about 10–55 nm. The buffer layer **1300** may be formed from Silicon Dioxide, such as a low temperature oxide (LTO). A low process

temperature, typically less than about 150 degrees C, is desirable to prevent interdiffusion of the alternating layers in the underlying ML mirror **1200**. Other materials, such as Silicon Oxynitride or Carbon, may be used to form the buffer layer **1300**. The buffer layer **1300** may be deposited by Radio Frequency (RF) magnetron sputtering.

Fourth, an absorber layer **1400** is formed over the buffer layer **1300**. An embodiment is shown in **Figure 1 (d)**. The absorber layer **1400** may be formed from about 45–125 nm of a material that will attenuate EUV light, remain stable during exposure to EUV light, and be compatible with the mask fabrication process. The absorber layer **1400** may be deposited with DC magnetron sputtering.

Various metals, alloys, and ceramics may be used to form the absorber layer **1400**. Metals include Aluminum, Chromium, Nickel, Tantalum, Titanium, and Tungsten. Alloys include compounds of metals, such as Aluminum-Copper. Ceramics include compounds of metals and nonmetals, such as borides, carbides, nitrides, oxides, phosphides, silicides, and sulfides of metals. Examples include Nickel Silicide, Tantalum Boride, Tantalum Germanium, Tantalum Nitride, Tantalum Silicide, Tantalum Silicon Nitride, and Titanium Nitride.

The combination of absorber layer **1400**, buffer layer **1300**, ML mirror **1200**, and substrate **1100** results in an EUV mask blank **1700**. An embodiment is shown in **Figure 1 (d)**. The EUV mask blank **1700** shown in **Figure 1 (d)** may be further processed to produce an EUV mask **1800**, an embodiment of which is shown in **Figure 2 (d)**.

First, an EUV mask blank **1700** is covered with a radiation-sensitive layer, such as photoresist **1600**. The photoresist **1600** has a thickness of about 160–640 nm. A chemically-amplified resist (CAR) may be used. A desired pattern is formed in the photoresist **1600** by selective exposure with sufficient radiation of the appropriate wavelength, such as DUV light or electron beam, followed by a wet or dry develop process. An embodiment is shown in **Figure 2 (a)**. After developing the pattern in the photoresist **1600**, the critical dimension (CD) of the

features is measured with an optical tool or a scanning electron microscope (SEM).

Reactive ion etch (RIE) may be used to transfer the pattern from the photoresist **1600** into the underlying absorber layer **1400**. For example, an absorber layer **1400** may be dry etched with a gas containing Chlorine, such as Cl_2 or BCl_3, or with a gas containing Fluorine, such as NF_3. Argon may be used as a carrier gas. In some cases, Oxygen may be included. The etch rate and the etch selectivity may be changed by modifying the configuration of the reactor chamber and adjusting parameters such as power, pressure, substrate temperature, and gas flowrate.

The buffer layer **1300** serves as an etch stop layer to help produce a good etch profile in the overlying absorber layer **1400**. Furthermore, the buffer layer **1300** protects the underlying ML mirror **1200** from damage during the etch of the overlying absorber layer **1400**. The buffer layer **1300** also protects the underlying ML mirror **1200** from damage during any subsequent repair to remove opaque defects in the absorber layer **1400**.

After completing the etch, the photoresist **1600** is removed and the CD of the features formed in the absorber layer **1400** is measured with an optical tool or with a scanning electron microscope (SEM). Whenever appropriate, an interferometer may be used to measure the phase of the light signals in addition to the amplitude. Then the mask is inspected for defects with a microscope or an automated inspection tool. The mask inspection tools may combine optical techniques with scanning of the mask to acquire images. A laser producing UV/DUV light is usually used as the source of illumination. Typical wavelengths include, but are not limited to, 488 nm, 365 nm, 266 nm, 257 nm, 248 nm, 198 nm, and 193 nm. A shorter wavelength provides better resolution and may be a better predictor of the lithographic consequences of the defects that are found on the mask.

Defect inspection is generally performed by comparing two nominally identical patterns printed in different portions of a mask (die-to-die) or comparing a pattern printed on the mask and the corresponding layout data for the pattern (die-to-database). A defect may be found in the absorber layer **1400** after pattern transfer from the photoresist **1600**. The defect may appear as a clear defect **1710** or as an opaque defect **1720**. An embodiment is shown in **Figure 2 (b)**. In a clear defect **1710**, the absorber layer **1400** should be present, but it is completely or partially missing. In an opaque defect **1720**, the absorber layer **1400** should be absent, but it is completely or partially present.

A focused ion beam (FIB) tool may be used to cover a clear defect **1710** with an opaque material **1730**, such as Carbon. A clear defect may also be repaired by ion beam-induced metal deposition from organometallic precursor gases. For example, Tungsten may be deposited from Tungsten Hexacarbonyl or $W(CO)_6$ gas. A post-deposition trim with gas-assisted etch (GAE) may be performed to eliminate any overspray and to achieve the desired post-repair size for the opaque material **1730**. Bromine gas or Chlorine gas may be used in the GAE. The deposited opaque material **1730** need not have the same thickness as the chrome on a transmissive mask or the absorber layer **1400** on a reflective mask. The deposited opaque material **1730** should be compatible with the chemicals used to clean the mask.

The present invention envisions using electron beam-induced chemical etching to repair an opaque defect **1720** on a DUV mask or an EUV mask. Electron beam-induced chemical etching has high selectivity to underlying layers because it is essentially chemical, unlike FIB or GAE, which always have a physical component due to the ion bombardment. Unlike with the ion beam in FIB, an electron beam will not damage underlying layers by ion implantation or by knock-on of atoms. An embodiment is shown in **Figure 2 (c)**.

In an EUV mask, a buffer layer **1300** covers and protects the ML mirror **1200** from damage during repair of the overlying absorber layer **1400**. The

thickness required for the buffer layer **1300** depends on the quantity of material that will be removed by the repair process. Consequently, a high etch selectivity allows the use of a thin buffer layer **1300** on an EUV mask. A thin buffer layer **1300** results in a lower overall absorber stack that reduces shadowing and improves imaging. A thin buffer layer **1300** also reduces the chances of generating printable soft defects during the removal of the buffer layer **1300** after completion of repair.

The buffer layer **1300** will increase light absorption over the ML mirror **1200** when the EUV mask **1800** is used to expose photoresist on a wafer. The result is a reduction in contrast that will slightly degrade CD control of the features printed in the photoresist on a wafer. In order to prevent this degradation, the buffer layer **1300** is removed wherever it is not covered by the absorber layer **1400**.

The overlying absorber layer **1400** and the underlying ML mirror **1200** must not be damaged when the exposed portions of the buffer layer **1300** are removed. A buffer layer **1300** formed from Silicon Dioxide may be dry etched with a gas containing Fluorine, such as CF_4 or C_5F_8. In some cases, Oxygen and a carrier gas, such as Argon, may be included. Alternatively, a thin buffer layer **1300** may be wet etched since any undercut of the absorber layer **1400** would then be small. For example, a buffer layer **1300** formed from Silicon Dioxide may be etched with an aqueous solution of about 3–5 % hydrofluoric acid. A combination of dry etch and wet etch may be used if desired.

The result of the process described above is an EUV mask **1800** having a reflective region **1750** and an anti-reflective, or dark, region **1760**. An embodiment is shown in **Figure 2 (d)**.

Another embodiment of the present invention is an EUV mask **2700** as shown in **Figure 3**. An EUV mask **2700** includes an absorber layer **2400**, a thin buffer layer **2300**, an ML mirror **2200**, and a substrate **2100**. The EUV mask **2700** has a first region **2750** and a second region **2760**. The first region **2750** is reflective

because the ML mirror **2200** is uncovered. The second region **2760** is anti-reflective, or dark, due to the absorber layer **2400**.

First, the EUV mask **2700** of the present invention includes a substrate **2100**, such as a glass-ceramic material, that has a low coefficient of thermal expansion (CTE), a low defect level, and a smooth surface.

Second, a multilayer (ML) mirror **2200** is disposed over the substrate **2100**. The ML mirror **2200** has about 20–80 pairs of alternating layers of a high index of refraction material **2210** and a low index of refraction material **2220**.

In one embodiment, the ML mirror **2200** includes 40 pairs of a high index of refraction material **2210** and a low index of refraction material **2220**. The high index of refraction material **2210** may be about 2.8 nm thick Molybdenum while the low index of refraction material **2220** may be about 4.1 nm thick Silicon. The ML mirror **2200** has a peak reflectivity of about 60-75 % at a central illumination wavelength of about 13.4 nm.

Third, an ultrathin buffer layer **2300** is disposed over the ML mirror **2200**. The ultrathin buffer layer **2300** is about 10–55 nm thick. The ultrathin buffer layer **2300** protects the underlying ML mirror **2200** from any damage during the etch of the overlying absorber layer **2400**. The ultrathin buffer layer **2300** also protects the underlying ML mirror **2200** from damage during repair to remove opaque defects.

The ultrathin buffer layer **2300** may be Silicon Dioxide, such as a low temperature oxide (LTO). Other materials, such as Silicon Oxynitride or Carbon may also be used for the ultrathin buffer layer **2300**.

Fourth, an absorber layer **2400** is disposed over the ultrathin buffer layer **2300**. The absorber layer **2400** may be about 45–125 nm of a material that will attenuate EUV light, remain stable during exposure to EUV light, and be compatible with the mask fabrication process.

The absorber layer **2400** may include one or more metals, alloys, and ceramics. Metals include Aluminum, Chromium, Nickel, Niobium, Tantalum, Titanium, and Tungsten. Alloys include compounds of metals, such as

Aluminum-Copper. Ceramics are compounds formed from metals and nonmetals, such as borides, carbides, nitrides, oxides, or silicides of various metals. Examples include Nickel Silicide, Tantalum Boride, Tantalum Germanium, Tantalum Nitride, Tantalum Silicide, Tantalum Silicon Nitride, and Titanium Nitride.

The present invention further envisions an apparatus **400** to repair an opaque defect **405** on a DUV or EUV mask **410**, by using electron beam-induced chemical etching. An embodiment is shown in **Figure 4**.

In the apparatus **400** claimed in the present invention, a mask **410** to be repaired is mounted on a holder **420**. The holder **420** is positioned in a chamber **470** by a stage **430**. The stage **430** can rotate, tilt, and move in different directions, such as along the x-axis, y-axis, and z-axis. An imaging system **440** is used to locate an opaque defect **405** on the mask **410**. The imaging system **440** may include an electron column.

A gas delivery system **450** dispenses one or more gases from reservoirs towards the opaque defect **405** on the substrate **410** in the chamber **470**. The gases may be fed through one or more openings, such as nozzles, into the chamber **470**. The desired flowrates are maintained by adjusting flow control valves.

Critical parameters include nozzle dimensions, tilt angle from nozzle to mask, angular dispersion of gas dispensed, and distance from the opening of the nozzle opening to the surface of the mask. Typical values include, but are not limited to, 100-300 microns (um) for nozzle diameter, 45-70 degrees (from vertical) for nozzle tilt angle, 5-25 degrees for angular dispersion, and 50-150 um for distance from the nozzle opening to the mask surface.

The gases may include reactant gases and carrier gases. The choice of reactant gases depends on the materials to be etched. In one embodiment of the present invention, the reactant gases adsorb to the opaque defect **405** and become dissociated. Argon is an example of a carrier gas.

In a DUV transmissive mask **410**, an opaque defect **405** may include materials such as chrome, chrome oxide, chrome nitride, or chrome oxynitride.

The underlying layer may include quartz. An electron delivery system **460** may be used to induce a reactant gas, such as chlorine (Cl_2) and oxygen (O_2), to chemically etch the opaque defect **405** relative to the underlying layer with a selectivity of 2:1 or more.

In an EUV reflective mask **410**, an opaque defect **405** may include absorber layer material such as Tantalum Nitride. The underlying layer may include buffer layer material such as Silicon Dioxide. An electron delivery system **460** may be used to induce a reactant gas, such as Xenon Fluoride (XeF_2) or Carbon Tetrafluoride (CF_4) or Fluorine (F_2), to chemically etch the opaque defect **405** relative to the underlying layer with a selectivity of 10:1 or more. Volatile byproducts, such as Tantalum Fluoride, may be removed from the chamber **470** by a pumping system **480**.

When an opaque defect **405** includes a Carbon-containing material, an electron delivery system **460** may be used to induce a reactant gas, such as water vapor (H_2O) or Oxygen (O_2), to chemically etch the opaque defect **405** relative to the underlying layer with a selectivity of 10:1 or more. For example, a Carbon etch may be used to repair an opaque defect **405** on an EUV mask **410** that has a conductive buffer layer containing Carbon. A Carbon etch may also be used to repair an opaque defect **405** in a photoresist pattern on a mask **410** to increase the patterning yield and to reduce rework. Furthermore, a Carbon etch may be helpful in the more difficult repair that is required after a mask **410** has gone through additional processing.

The electron delivery system **460** used to induce chemical etching may resemble an electron column used to image a sample in a SEM except that the focusing and scanning controls for the electron beam are more sophisticated. In particular, critical parameters, such as beam current, pixel spacing, dwell time, scan rate, refresh time, and retrace time, may be controlled by a computer to optimize etch rate, etch geometry, etch uniformity, and surface roughness.

The electron delivery system **460** directs electrons towards the opaque defect **405** on the mask **410** in the chamber **470**. The electron delivery system **460** may include a focusing system to provide a highly focused electron beam. In one embodiment, highly focused means that the electron beam size is smaller than the range of the secondary electrons. In another embodiment, highly focused means that the electron beam size is smaller than about 30% of the size of the smallest critical defect to be repaired. In general, an electron beam has a typical tail diameter of about 5-125 nm.

The electron delivery system **460** uses a low acceleration voltage, such as in the range of 0.3-3.0 keV, to limit the lateral spread of emitted electrons at the surface of the mask **410**. A low voltage also minimizes surface charging. The emitted electrons include secondary electrons and backscattered electrons. A chemical etch of an opaque defect **405** is induced when secondary electrons interact with the reactant gas that is adsorbed and dissociated on the surface of the mask **410**. If desired, the secondary electron current may be monitored to detect the etch endpoint.

In most cases, the electron beam-induced chemical etch is reaction-limited and not mass transfer-limited. The chemical etching of the opaque defect **405** by the reactant gas produces volatile byproducts that dissociate from the mask and may be removed from the chamber **470** holding the mask 410. A pumping system **480** evacuates gases and volatile materials from the chamber **470**, thus creating a vacuum inside the chamber **470**.

The electron beam-induced chemical etch rate of the opaque defect **405** depends on the partial pressure of the reactant gas and the current density of the electron beam. The pressure in the chamber **470** may be about 0.001-0.200 milliTorr (mT) globally and about 0.500-10.000 mT locally over the opaque defect **405** being repaired on the mask **405**. The beam current may be about 0.050-1.000 nanoAmperes (nA). The electron beam-induced chemical etch rate usually depends on the yield of the secondary electrons. The etch rate is usually at a maximum for an acceleration voltage of about 1.0 keV or less.

Many embodiments and numerous details have been set forth above in order to provide a thorough understanding of the present invention. One skilled in the art will appreciate that many of the features in one embodiment are equally applicable to other embodiments. One skilled in the art will also appreciate the ability to make various equivalent substitutions for those specific materials, processes, dimensions, concentrations, etc. described herein. It is to be understood that the detailed description of the present invention should be taken as illustrative and not limiting, wherein the scope of the present invention should be determined by the claims that follow.

Thus, we have described an apparatus for and a method of fabricating and repairing a mask without damage.